Implementing Marginal-Cost Vehicle Mileage Fees on the Maryland Statewide Road Network

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ABSTRACT

Vehicle mileage fees or similar user-based road charge could be an effective supplement or replacement of the current fuel tax on the nation’s highways and bridges. At the same time, properly structured mileage fee systems may help transportation professionals and officials at all levels address prominent issues such as funding gap, traffic congestion, and emissions. In theory, vehicles should be assessed a user fee equivalent to the full marginal cost not already borne by the users. This paper first estimates the full marginal cost of auto and truck travel in different time periods on all roadways in Maryland, and evaluates the impacts of such marginal-cost vehicle-miles-traveled fees (VMT fees) on travel behavior, revenue generation, equity, pollution, and GHG emissions both in Maryland and in the surrounding States of Delaware, Pennsylvania, Virginia, West Virginia, and the District of Columbia (DC). Results show that with consideration of all driving externalities, the marginal-cost VMT fee for auto (truck) travel in Maryland during
peak periods ranges from 0.20~12.16 (3.91~45.33) cents/mile. Compared to the existing revenue policy, the marginal-cost VMT fee can reduce overall vehicle miles traveled by 7.65% in the multi-state region covered by the quantitative model, by 7.81% just in Maryland. In addition, air pollution and GHG emissions in Maryland can be reduced by 7.62% to 9.42% by pollutant type. Total revenue generation would increase by about 168% from that under the existing revenue policy (including fuel taxes and sporadic bridge/roadway tolls). In terms of income equity, the middle-income group would be hurt the most with the largest consumer surplus decrease, while the highest income group is hurt the least. Results also indicate that the proposed marginal-cost VMT fee in Maryland can affect the neighboring states to varying degrees. For instance, vehicle miles traveled reduction ranges from 0.02% to 1.35% in the neighboring four states and DC, and their revenue generation changes by -1.48% to 0.15%.

1. INTRODUCTION

The Maryland state gasoline tax is 23.5 cents per gallon and 24.3 cents per gallon for diesel, and the federal gas tax remains at 18.4 cents per gallon since 1993. However, the gas tax is not a sustainable source for the transportation revenue and increasing gas tax is not politically popular. Consequently, tax collections are going down, due to the fact of the decreasing purchasing power of fuel tax, the vehicle efficiency increasing, the prevalence of electric and hybrid vehicles, more restrictive CAFE standards, and demographics and travel trends changes. As a result, the future revenues will be insufficient to fund transportation system. Alternative such as vehicle mileage fee is proposed and becomes a strong candidate to supplement or replace fuel taxes. Ideally, vehicles should be charged a user fee which takes into account the impacts of the vehicles on the environment, the road congestion, and the damage to the infrastructure when they are driven.
Such distance-based user charge can be thought as a good proxy for the optimal road pricing which charges users the marginal cost they impose on the road but not borne.

It is likely that the vehicle mileage fee or similar user-based charge would emerge over time as an effective replacement of the current gas tax for the nation’s highway, road system, and bridges. However, this change will not happen soon, and we will still largely depend on the gas taxes at both the federal and state levels for some time. Moreover, the political, financial, and technological hurdles to the introduction of a federal VMT charge seem substantial. Therefore, the transition of gas tax to VMT fee is likely to come from the bottom up, that is, the VMT fee will certainly be first introduced at the state or local level. In fact, it is likely for states to turn to such revenue sources, as federal funding for transportation continues to decline and to become more uncertain.

With the advance in the technologies such as Global Positioning Systems (GPS), Automatic Vehicle Identification (AVI), and improved tracking methods that protect the users’ privacy and place less burden on the users, the VMT fee would become increasingly feasible and attractive to policy makers and economists.

Given the aforementioned interests in revenue generation and distance-based user charge, it is innovative for this paper to develop a framework of full marginal-cost vehicle mileage fee at road link level by vehicle type and time period and to apply the estimated marginal-cost VMT fee in Maryland road network. In the end, the impacts of the VMT fee on people’s travel behavior, revenue generation, emissions, and equity are evaluated at various levels. The analysis is expected to assist the policy makers in determining the feasibility and the effectiveness of the decision.

2. LITERATURE REVIEW
VMT fees are viewed and explored by many researchers as an attractive alternative to replace the gas tax. Since it charges the users based on the travel distance, it makes the travelers accountable for their use of the roadway. Various pilot tests are carried on around the U.S. The Oregon Road User Fee Task Force (RUFTF) was established to select possible alternative fee/tax ideas and test them in pilot studies. The pilot program (2006-2007) demonstrated the feasibility of implementing VMT fee and collecting VMT fee electronically during refueling. The technology associated with the pilot test is examined and determined to be capable of collecting VMT fee without placing drivers’ and system operators’ extra burden. Minnesota DOT conducts studies on mileage-based fees. And in April, 2011 they established a policy task force to identify and evaluate policy implications of potential implementation of a Mileage-Based User Fee (MBUF) system in Minnesota in future. State-wide and full-scale implementation of mileage-based user fee is not suggested in the task force since the mileage-based user fee is not familiar to the public and complex in terms of technique and policy. The Public Policy Center at the University of Iowa conducts a four-year study to explore the technological feasibility and public acceptance of road user fees. The study places an on-board computer in participant’s vehicle, and the GPS located in the on-board computer tracks the number of miles the participant travels and reports to the PPC to be processed and evaluated. Participants are selected from regions across the county and range from urban to rural in age, education and background.

Previous studies have also done research on mileage fee designing and the impacts of the mileage fee on people’s travel behavior, revenue generation, emissions, and equity. Zhang (2009) conducted a research using 2001 National Household Travel Survey (NHTS) data to estimate the equity impacts of a flat VMT fee (1.2 cents per mile) by both household income level and residential locations in short term and long term. Similarly, Zhang and McMullen introduced two
green VMT fees and two flat VMT fees, running each scenario statistically and dynamically using 2001 NHTS data. West, Parry and Small found mileage fee to be a better instrument for approximating the optimal per-mile emissions fee than gasoline tax. Accordingly, mileage fee for road users may have the additional social benefit of reducing emissions. Weatherford examined the equity impacts of an equivalent flat VMT fee of $0.98 per mile instead of the federal gas tax. The proposed VMT fee places a less tax burden on low-income households, rural households, and retired households. They suggested that future VMT fee should consider methods to encourage the use of high fuel-efficient vehicles while positive equity impacts for low-income and rural households are maintained. Zhang and Methipara proposed three green mileage fee options including green mileage fee by vehicle fuel economy, mileage-based emission tax based on vehicle greenhouse gas and pollution emission ratings, and a variable mileage fee by regional congestion levels. The impacts of the three proposed financing policies on revenue collection, energy/environmental sustainability, congestion, and equity are estimated at both the national level and the state level. Results of the study indicate that the three proposed policies have the similar distributional impact to that of the existing gas tax.

3. FULL MARGINAL COST ESTIMATION

Road pricing in the U.S mainly focuses on either revenue generation for transportation system maintenance or congestion pricing for demand management. The optimal road user charge that accounts for all society costs is sustainable in transportation system. In general, economists support a mileage fee requiring road users to pay all costs imposed on society but not borne by them, which means that a true estimate of the burden of one additional vehicle on the roadway system and all other users is required. The marginal-cost VMT fee we proposed will charge users the full marginal cost of the vehicle they drive in each roadway segment during peak and off-
peak periods. The marginal cost in our research considers all driving externalities including pavement maintenance, travel time, emissions, safety, vehicle operation and noise.

Highway Economic Requirements Systems (HERS) provides a solid framework to calculate the five component costs, except noise cost, of the vehicles marginal cost for each roadway across the nation by interfacing with Highway Performance Monitoring System (HPMS) database. In addition to HERS, the noise cost is obtained based on the work conducted by Haling and Cohen. Each of the components is obtained separately for seven types of vehicles (small automobiles, medium-large automobiles, pickups and vans, six-tire single-unit trucks, three and four axle single-unit trucks, four axle combined trucks, and five axle combined trucks) during peak and off-peak periods.

The HERS system consists of seven principle models: pavement condition, speed estimation, vehicle operation cost, emission cost, travel time cost, agency cost, and safety cost. The estimation results of the seven models either provide the five component costs of the full marginal cost (emission cost, vehicle operation cost, travel time cost, agency cost, and safety cost) or act as an intermediate model for other models to obtain the component marginal cost (pavement condition and speed estimation). HERS first estimates pavement conditions by executing the pavement condition model. Secondly, the effective speed of each vehicle is estimated by the speed sub-model, and passed onwards into the sub-models of emission cost, vehicle operation cost, and travel time cost. Thirdly, the agency cost sub-model uses the forecasted pavement condition to derive costs for resurfacing roadway sections. Lastly, the safety cost model estimates property damage, injury and fatality costs independently of the other models. In addition, the noise cost model based on Haling and Cohen’s work utilizes the vehicle’s average effective speed to estimate the noise damage. Since the methodology uses the
HPMS to estimate the vehicle marginal cost on individual segment of roadway, the marginal cost is only calculated for the roadways that are sampled. Then, these roadways are expanded using HPMS sample expansion factors.

Once the component cost for each roadway has been obtained, the marginal cost of adding one additional vehicle of a specific vehicle type can be iteratively calculated. An increase of any type of vehicle volume will yield a change in the pavement condition, travel time, emissions and so on, which will in turn affect the component costs of the full marginal cost. Therefore, the simple way to calculate the total marginal cost is to take the difference between the initial base cost and incremented volume cost. Since the total marginal cost provides the estimates of the impacts to the entire society and the additional road users already pay some of the burden such as vehicle insurance, vehicle maintenance, and travel time, the pre-paid average user cost needs to be subtracted from the total marginal cost. Consequently, the marginal cost as an estimate of per mile fee can be described in equation (1).

\[ \text{Marginal Cost to Society} = (MC_p + MC_s + MC_e + MC_{tt} + MC_{op} + MC_{ns}) - (AVGs + AVGtt + AVGop) \] (1)

- **MCₚ**: Marginal agency pavement maintenance cost, cents/mile;
- **MCₛ**: Marginal safety cost, cents/mile;
- **MCₑ**: Marginal emission cost, cents/mile;
- **MCₜₜ**: Marginal travel time cost, cents/mile;
- **MCₒp**: Marginal vehicle operation cost, cents/mile;
- **MCₙₙ**: Marginal vehicle noise cost, cents/mile;
- **AVGₛ**: Average safety cost, cents/mile;
- **AVGₜₜ**: Average travel time cost, cents/mile;
AVG$_{\text{op}}$: Average vehicle operation cost, cents/mile;

The pavement condition sub-model employed by HERS assumes that the pavement damage is caused by both the vehicle traffic and the weather conditions. It uses a three-step procedure to forecast the pavement condition. First, the effects of vehicle traffic on a section’s PSR (present serviceability rating) are calculated. Then, a maximum and a minimum deterioration rate are obtained separately: the maximum deterioration rate is developed based on the structural number for the corresponding pavement type reported in HERS, and the minimum deterioration rate is obtained according to the natural deterioration associated with the weather. Finally, HERS applies the maximum and minimum rates to the current PSR value to derive the forecast pavement condition. Once the pavement condition is obtained through the pavement model, it is forwarded to the agency cost sub-model.

The HERS speed sub-model is employed to help to derive the travel time, vehicle operation and emission costs. It takes into account the impacts of the pavement curvature, roughness, grades, the posted speed limit, types, and the number of traffic control devices at intersections on the speed during the periods of off-peak, peak in peak direction, and peak in counter-peak direction. Models based on Texas Research and Development Foundation (TRDF) adaptation of the "Aggregate Probabilistic Limiting Velocity Model" (APLVM) in conjunction with algorithms from both Science Applications International Corporation (SAIC) and Cambridge Systematics are adopted to estimate the average effective speed for later use in the sub-models of the travel time cost, vehicle operating cost, and vehicle emission cost.

3.1 Safety Cost

HERS safety model, independent of the other HERS sub-models, adopts a three-step procedure to estimate the safety cost. First, the number of crashes in 100-million vehicle miles is estimated
according to the crash rate equations recommended by Richard Margiotta’s report to FHWA Incorporating Traffic Crash and Incident Information into the Highway Performance Monitoring System Analytical Process along with Vogt Bared’s Accident Models for Two-Lane Rural Segments and Intersections. The crash rates are estimated for six parts which are classified based on both urban/rural and facility type (freeway, multi-lane roads, two-lane roads). Secondly, the injury/crash ratios and fatality/crash ratios of each functional system from 1995 Highway Statistics are applied to estimate the number of injuries and fatalities per crash by functional system. Finally, multiplying the number of injuries and fatalities by cost parameters will give the cost per crash in term of injuries, fatalities, property damage, and delay. For a specific road segment, the overall crash cost is shown in function (2).

\[ SCST = N_{crs} \times R_{inj/crs} \times UCST_{inj} + N_{crs} \times R_{fat/crs} \times VOL + N_{crs} \times (UCST_{pt} + UCST_{Dy}) \]  

(2)

Where \( SCST \) is the total crash cost per 100 million vehicle miles; \( N_{crs} \) is the number of crashes per 100 million vehicle miles; \( R_{inj/crs} \) is the number of injuries per crash; \( R_{fat/crs} \) is the ratio of fatalities per crash; \( UCST_{inj} \) is the injury cost per injury; \( VOL \) is the value of life per person; \( UCST_{pt} \) is the property damage cost per crash; \( UCST_{Dy} \) is the travel delay cost per crash.

Injury costs are derived from estimates of comprehensive costs per injury developed by Ted Miller in 1991 dollars and later updated to 1994 dollars by National Highway Traffic Safety Administration. Estimates of property damage costs and travel delay costs are also derived from the NHTSA and HERS crash estimation and calibration procedure. The U.S. Department of Transportation's estimate of the value of life helps to derive the cost of fatalities. These costs are then indexed from 1994 dollars to those in future years with property damage cost indexed by Consumer Price Index and delay and injury costs indexed by the Bureau of Labor Statistics Employment Cost Index.
3.2 Emission Cost

The total emissions cost by vehicle type is estimated using HERS based on the average effective speed from the Speed model. First, the Environment Protection Agency’s MOBILE6 is used to estimate the emission rate by speed, vehicle type, and pollutant type (carbon monoxide, sulfur oxides, nitrogen oxides and particulate matter less than 2.5 microns). Per ton damage costs for each pollutant type are scaled based on the rural and urban area, due to the fact that the higher population exposure to emissions in urban areas than that in rural areas. Finally, the total emission costs can be achieved by multiplying the selected emission cost per vehicle according to the speed and vehicle type by the respective volume of vehicles (vehicles with same speed and vehicle type) and then summing across all total vehicle emission costs.

3.3 Travel Time Cost

HERS computes the travel time cost by vehicle type based on the average effective speed from the speed model. According to HERS, the average travel time cost per thousand vehicle miles in 1995 dollars can be described in function (3)

\[
TTCST_{vt} = \frac{1000}{AES_{vt}} \times TTVOT_{vt}
\]  

(3)

Where \(TTCST_{vt}\) is the average travel time cost for vehicle type \(vt\); \(AES_{vt}\) is the average effective speed of vehicle type \(vt\) from the speed sub-model; \(TTVOT_{vt}\) is the average value of time for occupants and cargo of vehicle type \(vt\).

To estimate the travel time cost, HERS incorporates the values of time per person for personal and business travel according to the U.S. Department of Transportation’s Departmental Guidance report from 1997. In order to index the value of time from 1997 dollars to a subsequent year, HERS employs separate operations of value of time per person, per vehicle cost, and per inventory cost. The three indexes used for the three components are the U.S. Bureau of Labor
Statistics (BLS) Employment Cost Index for total compensation of all civilian workers, U.S. Department of Commerce Bureau of Economic Analysis (BEA) data on average expenditures per car, and the implicit gross domestic product (GDP) price deflator. Given a specific vehicle type, the average value of time TTVOT can be indicated in function (4)

\[
TTVOT = \sum_{i=1}^{2} P_i \times (VOT_i \times VC_i + VehCST_i + InvCST_i)
\]  

Where \( i=1 \) indicates business travel and \( i=2 \) indicates personal travel; \( P_i \) is the percentage of travel type \( i \); \( VOT_i \) is the value of time per person for travel type \( i \); \( VC_i \) is the average vehicle occupancy for travel type \( i \); \( VehCST_i \) is the vehicle depreciation cost for travel type \( i \), which is a time-related cost due to the natural aging, and therefore, is different from the mileage-related depreciation cost in vehicle operation cost. \( InvCST_i \) is the inventory cost for travel type \( i \).

3.4 Vehicle Operation Cost
HERS considers five components of operating costs including fuel consumption, oil consumption, tire wear, maintenance and repair, as well as depreciable value. All the five components are included in the estimation of three sub-operating costs: constant-speed operating cost, excess operating cost due to speed changes, and excess operating cost due to curves. The estimation of constant-speed operating cost relies on the average effective speed (AES) acquired from the speed model, average grades, and pavement conditions (PSR) from pavement condition model. For each vehicle type, constant-speed operating cost is estimated as the sum of five components representing costs for fuel, oil, tires, maintenance and repair, and vehicle depreciation shown in function (5).

\[
CSCST = \sum_i ADJ_{pi} \times ADJ_i \times CR_i \times UCST_i
\]  

Where \( i \) indicates one of the five components (fuel, oil, tires, maintenance and repair, and vehicle depreciation); \( CSCST \) is the constant speed operating cost; \( ADJ_{pi} \) is the pavement condition
adjustment factor for component i; $ADJ_i$ is the adjustment factor of the corresponding component i; $CR_i$ is the constant speed consumption rate for component i; $UCST_i$ is the unit cost of component i.

Using a formula similar to that of the constant-speed cost function (5) and equations derived from Zaniewski’s report using ordinary least squares regression, HERS can estimate the excess operating cost due to speed changes. As to the operating cost due to curves, two approaches are used by HERS with one for sections having less than 55 mph average effective speed and the other one for sections having more than 55 mph AES.

Once the constant-speed operating cost, excess operating cost due to speed changes, and excess operating cost due to curves are calculated for each vehicle, the resulting costs are summed and multiplied by the estimated fleet composition to acquire a total fleet operating cost.

3.5 Agency Cost

Agency cost model derives the costs of resurfacing the roadway sections using the forecasted pavement condition from the output (PSR) of HERS’s pavement condition model. It estimates per lane mile maintenance cost in 1984 dollars by employing a regression equation based on Witczak and Rada’s Microcomputer Solution of the Project Level PMS Life Cycle Cost Model. The model develops the cumulative maintenance cost as a function of the pavement structural number (SN) and PSR. The final per lane mile maintenance cost is indexed from 1984 dollars to 1997 dollars using the index of 1.231 for rural sections and 1.242 for urban sections.

3.6 Noise Cost

HERS does not provide any cost models for noise damage estimation. Based on models developed by Haling and Cohen in 1997, our research combines noise generation and hedonic cost modeling. First, the total noise output of a specific vehicle type is estimated at three noise
ranges (40ft, 60ft and 80ft from the receiver to the source) and then aggregated for the entire vehicle fleet. The hourly noise level per vehicle type is described as a function of distance between the source and the receiver, average effective speed, and passenger car equivalent volume of the vehicle type. Second, the total hourly noise levels are converted to noise cost using hedonic price computations. The noise cost for a specific vehicle type is

\[ NSCST = \sum_{R=1}^{3} [H_R \times (N_{LR} - ND)] \times P \times Val_{prt} \]  

(6)

Where R indicates the three noise ranges; \(H_R\) is the housing units affected by noise at noise range R; \(N_{LR}\) is the total noise level by vehicle type at noise range R; \(ND\) is the noise threshold; \(P\) is percentage housing value per decibel; \(Val_{prt}\) is the average property value for county. The property value change per decibel is obtained based on a number of studies conducted in the 1970s and 1980s capturing the willingness to pay for lower noise levels. A damage approximation of 4% of the housing value per decibel above the threshold is obtained from Haling and Cohen’s work.

4. MARGINAL-COST VMT FEE FRAMEWORK

The estimated marginal-cost VMT fee for auto travel in Maryland during peak periods ranges from 0.20 cents/mile to 12.16 cents/mile (Figure 1), while the marginal-cost VMT fee for truck travel during peak periods ranges from 3.91 cents/mile to 45.33 cents/mile (Figure 2). Due to the space limitation, the marginal-cost VMT fee during off-peak periods is not presented.

The two figures show that almost all the interstate roadways, freeways, and expressways tend to have larger marginal-cost VMT fee for both auto and truck. However, most sections of interstate roadways with larger traffic volume such as I-495, I-95 between Washington D.C. and Baltimore, and I-95 between I-695 and Maryland Route 152 experience less auto marginal-cost VMT fee during peak period compared to those in most sections of interstate roadways such as I-
70, I-270, I-695 and I-97 (Figure 1). It can be concluded from the fact that the auto travel time marginal cost and noise cost for a large number of sections in I-70, I-270, I-695 and I-97 is larger than those in most sections of I-495 and I-95 (Washington D.C- Baltimore, I-695 - Maryland Route 152). In addition, the auto marginal cost VMT fee in some freeways and expressways such as US50, US29, Maryland Route 100 and 295 appears to be a little larger than that in most sections in I-495 and I-95 (Washington D.C. – Baltimore, I-695 - Maryland Route 152), which is resulted from the slightly larger vehicle operating marginal cost and emission cost. Meanwhile, the truck marginal cost VMT fee for almost all the interstate roadways tends to be larger than that of freeways and expressways (Figure 2). Particularly, the truck marginal-cost VMT fee during peak period in I-495, I-95, and I-695 are larger in general than that in I-70, US50, US29, and Maryland Route 100 and 295. Compared to auto marginal-cost VMT fee, the pavement maintenance marginal cost takes a dominant role in truck marginal-cost VMT fee. Hence, the comparatively smaller total truck marginal cost VMT fee in most sections of I-70, US50, US29, and Maryland Route 100 and 295 can be explained by the smaller pavement maintenance marginal cost.
FIGURE 1 Marginal Cost VMT fee for Auto during Peak Period

FIGURE 2 Marginal Cost VMT fee for Truck during Peak Period
5. EVALUATING THE IMPACT OF MARGINAL-COST VMT FEE IN MARYLAND

The proposed marginal-cost VMT fee framework is analyzed for the entire state of Maryland and its surrounding states with the Maryland Statewide Transportation Model (MSTM), developed by the Maryland State Highway Administration and the University of Maryland. The MSTM works at Regional, Statewide, and Urban levels. The Regional model covers North America, and contains 151 Regional Model Zones (RMZs). On the other hand the Statewide model includes 1588 Statewide Model Level zones (SMZs) that cover Maryland, Washington DC, Delaware and part areas of Pennsylvania, New Jersey, Virginia and West Virginia.

The MSTM is a four-step transportation model designed to generate link-level assignment for personal travel and freight travel. In terms of personal travel, the Statewide level models the short-distance or urban personal trips for study area residents. The statewide personal trips combined with long-distance trips for all residents and visitor trips over 50 miles included in Regional Level are modeled using a trip generation, trip distribution, and mode choice procedure. The trip production and attraction are derived based on the population data, households data (from Census 2000), employment data (from MPO TAZ data), and Quarterly Census Employment and Wages (QCEW) data for Maryland and etc. Then, the trip distribution adequately allocates the trips between O-D pairs. Further, the mode choice model splits the trips based on generalized utility functions for auto and transit travel. In terms of freight travel, long-distance truck trips into/out of and through the study area are generated by commodity flow data given by the Federal Highway Administration of the U.S. DOT in the Freight Analysis Framework (FAF). These trips are generated for the entire U.S., and further disaggregated to SMZ within the study area. These regional truck trips are integrated with short-distance truck trips estimated at the Statewide level using a trip generation and distribution method. The
personal trips and truck trips at both the Regional level and Statewide level provide the traffic flows to be assigned to a time period (AM Peak, AM Off-Peak or Middle Daytime, PM Peak, PM Off-Peak, or Night Time), and then are forwarded to the MultiClass Assignment that provides the shortest path in terms of user cost to the O-D pairs. For additional information about the MSTM, the readers are referred to *Maryland Statewide Transportation Model (MSTM)* by Maryland State Highway Administration.

6. POLICY ANALYSIS RESULTS

To implement the calculated marginal-cost VMT fee in MSTM, we replace the existing toll framework in Maryland with the one based on the calculated per mile marginal-cost VMT fee for both auto and truck in all roadway sections during different time periods, while all the other tolls outside Maryland are kept unchanged. A number of performance measures such as VMT changes at multiple levels, traffic volume, consumer surplus changes by income group, revenue generation, and GHG emissions and air pollutions are developed in order to examine the effectiveness of the proposed marginal-cost VMT fee.

If the marginal cost VMT fee incorporating the external costs of pavement maintenance, vehicle operation, travel time, safety, emission, and noise are applied based on MSTM, the overall daily vehicle miles travel at regional and statewide levels will be reduced by 7.65%, while the auto travel distance can be decreased by up to 8% and truck travel distance decreased by more than 3%.

Although the marginal cost VMT fee is only implemented in Maryland, it will definitely affect the people’s travel behavior in the neighboring states to some extent. Figure 3 illustrates the daily traffic volume change by road link at the statewide level covering Maryland, Washington DC, Delaware, and part of Pennsylvania, New Jersey, Virginia and West Virginia.
The figure illustrates that almost all the interstate roadways, freeways and expressways lying in Maryland can achieve a traffic volume reduction (both auto and truck) with the largest up to 40835, while some arterial and collector roads experience an increase in traffic volume with the highest up to 17487. A lot of road links with increased traffic volume can be found concentrated in the arterial and collector roads inside the interstate loop I-695 (Baltimore city) and near Baltimore, which can be explained by the lower marginal cost VMT fee of those roads, people’s sensitivity to the travel cost, higher density of population in Baltimore, as well as the dense road network which can provide the possibility for people to switch. In the surrounding states, a slight traffic volume change between -101 and 574 can be acquired for most of the road links.

Moreover, the daily revenue change by road link at the statewide level is displayed in Figure 4. The revenue collection in the research contains both the gas tax revenue and toll revenue for auto and truck. Figure 4 indicates that almost all the road links in Maryland have an increased revenue generation to various degrees except for a small number of local road links, which serves the lowest level of vehicle mobility, with little revenue generation change. It can be concluded, from Figure 4, that Washington DC and Delaware experience a slight revenue reduction. However, it is hard to distinguish whether the overall revenue increases or decreases in the neighboring states from the link-level revenue change.
FIGURE 3 Daily Traffic Volume Change at Statewide Level

FIGURE 4 Daily Revenue Change at Statewide Level
Based on the link-level traffic volume changes and the network characteristics, we can obtain the aggregated changes in vehicle mile travel by county in Maryland (Figure 5). A variation of vehicle miles reduction from 1.24% to 12.7% is acquired, with the smallest reduction in Cecil County and the largest in Howard County. The counties adjacent to Delaware experience less vehicle miles travel reduction in general compared to those adjacent to Washington D.C., Virginia and West Virginia. Since those counties where residents tend to have less entertainment activity and public facilities are more rural, most part of people’s travel is more likely to maintain their daily life. Therefore, the marginal-cost VMT fee implementation could not make them reduce much of their main travel for daily life.

**FIGURE 5 Percentage Changes of VMT by county in Maryland**

Furthermore, the effects of the marginal-cost VMT fee on vehicle miles travel, revenue generation, air pollution, and GHG emission are also reflected and represented at state level (Table 1). The vehicle miles travel in Maryland is significantly decreased by 7.805%, while the
neighboring states experience a slight vehicle miles reduction with the largest (1.352%) in Washington DC, which is consistent with the link-level traffic volume change (Figure 3). The vehicle miles travel reduction in the surrounding states can be explained by the fact that people in Maryland will travel less if the marginal-cost VMT fee is implemented, and their travel generated from Maryland to the surrounding states will definitely be affected, meanwhile, people in the surrounding states with the knowledge of the VMT fee will also decrease their travel to Maryland. Although vehicle miles travel will decrease in Maryland, the revenue including both toll and gas tax in the state can reach up to 2.68 times of the revenue under the existing toll policy. The surrounding states experience the similar revenue change pattern to the vehicle miles travel change except Pennsylvania with a little increase by 0.150% and Delaware with much larger reduction (1.483%). The increased revenue generation in Pennsylvania is the result of the increased truck vehicle miles travel and the truck’s lower fuel efficiency. A decreased revenue generation to a larger degree is experienced by Delaware, due to the highest tolled highway (Delaware Turnpike or John F. Kennedy Memorial Highway) in Delaware (up to $3) and decreased traffic volume in the highway.

In addition, Table 1 presents the impacts of the proposed marginal-cost VMT fee on air pollution and GHG emission in different states. Similar to the change in vehicle miles travel, the air pollution (CO, NO\textsubscript{x}, PM\textsubscript{10}) and GHG emission (CO\textsubscript{2}) in all the states can be reduced, while the largest reduction will be observed in Maryland.
TABLE 1 Percentage Change of Different Measurements by State

<table>
<thead>
<tr>
<th>State</th>
<th>VMT</th>
<th>Revenue</th>
<th>CO</th>
<th>NOx</th>
<th>PM10</th>
<th>CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maryland</td>
<td>-7.805%</td>
<td>168.222%</td>
<td>-7.621%</td>
<td>-9.142%</td>
<td>-9.419%</td>
<td>-7.803%</td>
</tr>
<tr>
<td>District of Columbia</td>
<td>-1.352%</td>
<td>-1.082%</td>
<td>-1.378%</td>
<td>-1.333%</td>
<td>-1.299%</td>
<td>-1.362%</td>
</tr>
<tr>
<td>Virginia</td>
<td>-0.342%</td>
<td>-0.238%</td>
<td>-0.361%</td>
<td>-0.291%</td>
<td>-0.295%</td>
<td>-0.334%</td>
</tr>
<tr>
<td>West Virginia</td>
<td>-1.018%</td>
<td>-1.201%</td>
<td>-1.025%</td>
<td>-1.565%</td>
<td>-1.585%</td>
<td>-1.184%</td>
</tr>
<tr>
<td>Delaware</td>
<td>-0.043%</td>
<td>-1.483%</td>
<td>-0.046%</td>
<td>-0.049%</td>
<td>-0.056%</td>
<td>-0.040%</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>-0.021%</td>
<td>0.150%</td>
<td>-0.036%</td>
<td>0.041%</td>
<td>0.019%</td>
<td>-0.005%</td>
</tr>
</tbody>
</table>

After the people’s travel behavior responses are evaluated under the proposed marginal-cost VMT fee, the changes in consumer surplus as a percentage of household income during different time periods per year can be estimated (Figure 6). Without the middle-income group, the monotonic increase of the consumer surplus reduction from the lowest income group to the highest income group can be achieved during all the time periods. However, the middle-income group experience the greatest reduction in consumer surplus change with the largest by up to 0.9% during middle daytime, which is caused by their larger travel distance shown in Figure 7 where Base means the base case scenario and MCMF indicates the marginal-cost VMT fee scenario. By contrast, the highest income group experience the least reduction in consumer surplus change during all time periods.
7. CONCLUSION

Researchers and decision-makers have agreed on the sustainability of mileage-based fee for financing the transportation system, reducing air pollution and GHG emission, and alleviating congestion. Therefore, this paper innovatively develops the theoretically sound and promising methods to estimate the full marginal-cost VMT fee at road link level by vehicle type during different time periods. The full margin cost incorporating pavement maintenance, vehicle...
emissions, vehicle operating, safety, travel time, and noise is estimated mainly based on HERS combined with HPMS database. Consequently, a range of 0.2 cents/mile to 12.16 cents/mile marginal-cost VMT fee can be acquired for auto driving in Maryland roadways during peak periods, and a range of 3.91 cents/mile to 45.3 cents/mile for truck can be obtained.

The calculated marginal-cost VMT fee is applied to the Maryland roadway system through the travel demand model MSTM as a supplement of existing gas tax. The impacts, at various levels, of the proposed marginal-cost VMT fee on travel behavior, revenue generation, equity, and air pollution and GHG emission are analyzed. The implementation of marginal-cost VMT fee would cause a reduction of 7.65% in overall vehicle miles travel at both regional and state levels, while only Maryland can experience a significant reduction by 7.805%, with a variation by county from 1.24% to 12.7%. Moreover, the air pollution and GHG emission can be decreased by from 7.621% to 9.419% in Maryland under the scenario of marginal-cost VMT fee. Thanks to the marginal-cost VMT fee, Maryland revenue generation does not deteriorate, although the vehicle miles travel is decreased. On the contrary, the revenue generation is 2.6 times as much as that under the existing policy. In terms of equity, the highest income group will hurt the least during any time periods, while the middle-income group will hurt the most with the largest consumer surplus decrease by 0.9% in middle daytime. In addition, the proposed marginal-cost VMT fee will affect the surrounding states to various degrees, with the vehicle miles travel reduction ranging from 0.021% to 1.352%, the revenue generation change from -1.483% to 0.150%. Air pollution and GHG emission reduction follows the similar pattern of vehicle miles travel reduction. Such a less aggressive marginal-cost VMT fee as a supplement of gas tax that produces necessary revenue, mitigates congestion, and reduces air pollution and GHG emission to a reasonable degree, can provide politicians and decision-makers the insight
and guide to develop a feasible, practical, and effective mileage-based fee framework at the state level.

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